Lecture slides for

Automated Planning: Theory and Practice

Chapter 4
State-Space Planning

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CMSC 722, AI Planning

University of Maryland, Fall 2004

Motivation

- Nearly all planning procedures are search procedures
- Different planning procedures have different search spaces
  - Two examples:
- *State-space planning*
  - Each node represents a state of the world
    - » A plan is a path through the space
- *Plan-space planning*
  - Each node is a set of partially-instantiated operators, plus some constraints
    - » Impose more and more constraints, until we get a plan

Outline

- State-space planning
  - Forward search
  - Backward search
  - Lifting
  - STRIPS
  - Block-stacking

Forward-search(O, s_0, g)

    $s \leftarrow s_0$

    $\pi \leftarrow$ the empty plan

    loop

        if s satisfies g then return π

        $E \leftarrow \{a | a$ is a ground instance an operator in O,

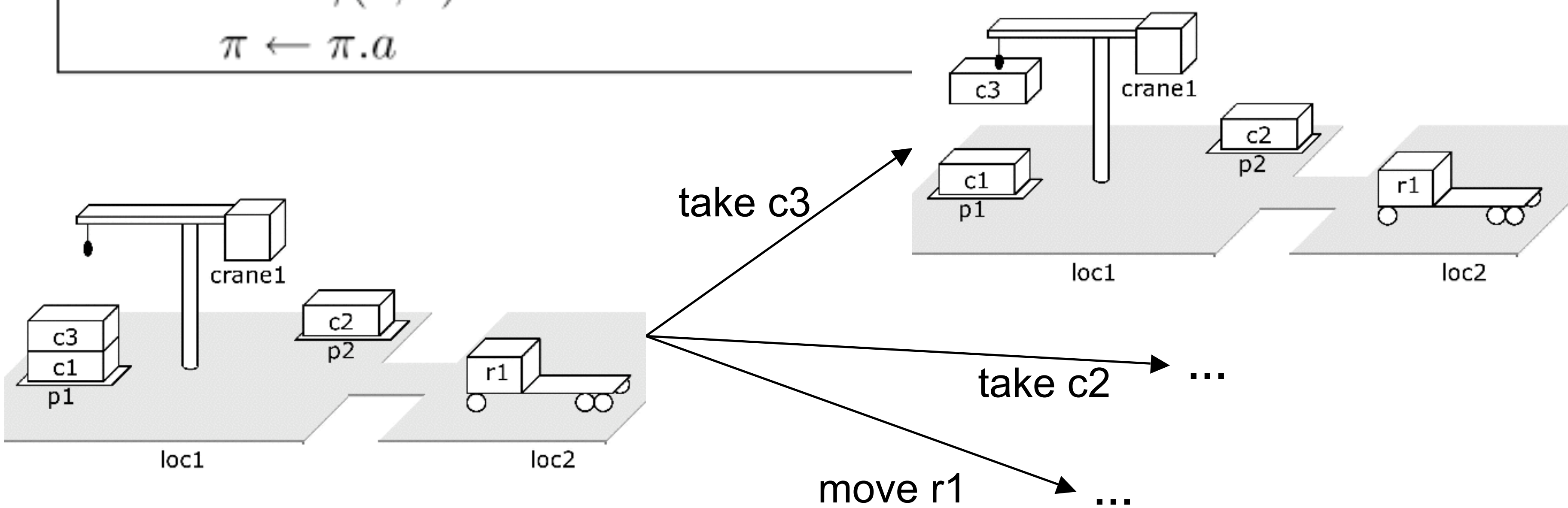
                and $\mathrm{precond}(a)$ is true in $s\}$

        if $E = \emptyset$ then return failure

        nondeterministically choose an action $a \in E$

        $s \leftarrow \gamma(s, a)$

        $\pi \leftarrow \pi.a$

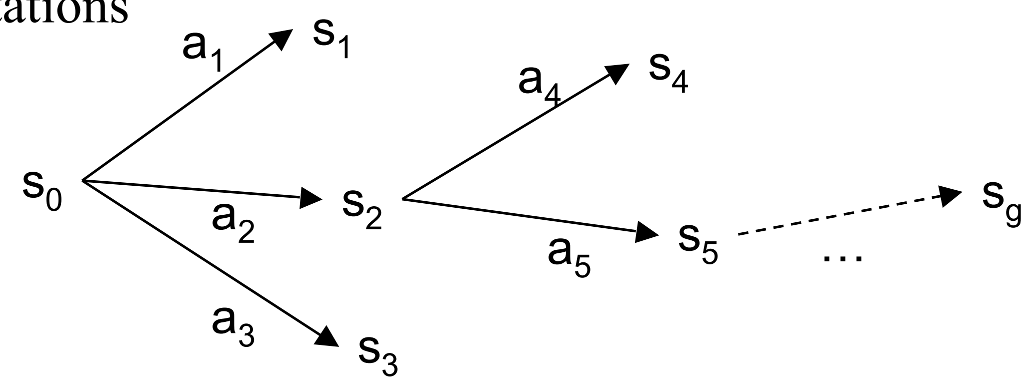


Properties

- Forward-search is *sound*
  - for any plan returned by any of its nondeterministic traces, this plan is guaranteed to be a solution
- Forward-search also is *complete*
  - if a solution exists then at least one of Forward-search's nondeterministic traces will return a solution.

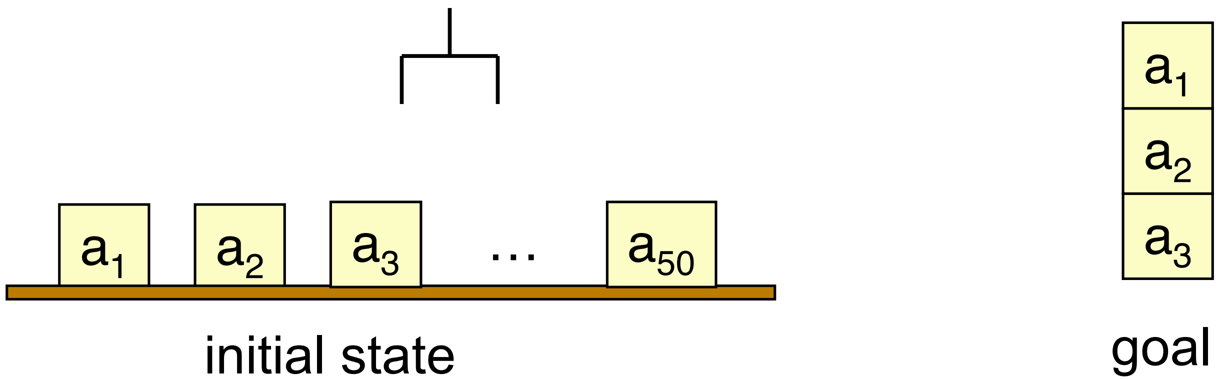
Deterministic Implementations

- Some deterministic implementations of forward search:
  - breadth-first search
  - best-first search
  - depth-first search
  - greedy search



- Breadth-first and best-first search are sound and complete
  - But they usually aren't practical because they require too much memory
  - Memory requirement is exponential in the length of the solution
- In practice, more likely to use a depth-first search or greedy search
  - Worst-case memory requirement is linear in the length of the solution
  - Sound but not complete
    - » But classical planning has only finitely many states
    - » Thus, can make depth-first search complete by doing loop-checking

Branching Factor of Forward Search



- Forward search can have a very large branching factor (see example)
- Why this is bad:
  - Deterministic implementations can waste time trying lots of irrelevant actions
- Need a good heuristic function and/or pruning procedure
  - See Section 4.5 (Domain-Specific State-Space Planning) and Part III (Heuristics and Control Strategies)

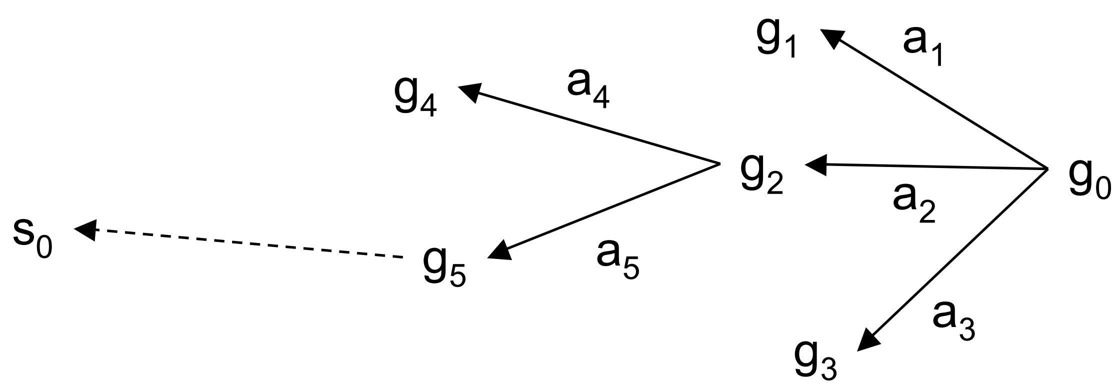
Backward Search

- For forward search, we started at the initial state and computed state transitions
  - new state = $\gamma(s,a)$
- For backward search, we start at the goal and compute inverse state transitions
  - new set of subgoals = $\gamma^{-1}(g,a)$

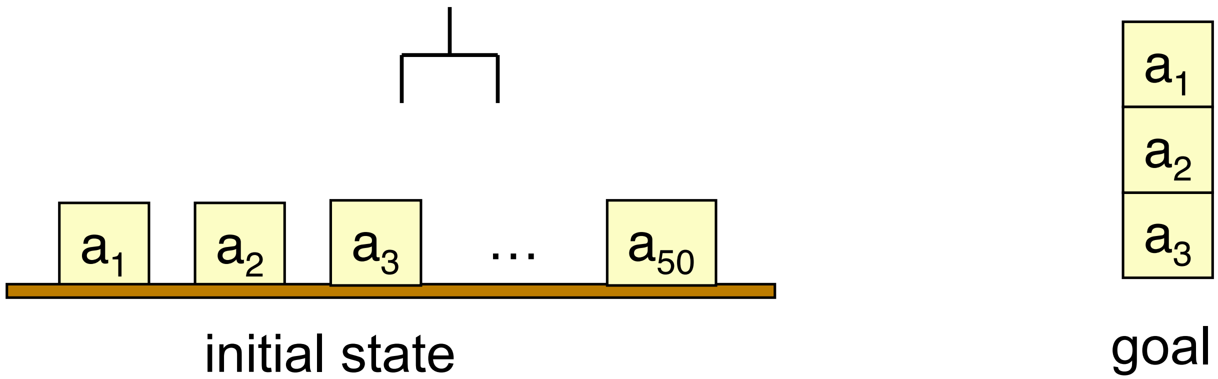
Inverse State Transitions

- What do we mean by $\gamma^{-1}(g,a)$?
- First need to define *relevance*:
  - An action a is relevant for a goal g if
    - a makes at least one of g's literals true
      - $g \cap \text{effects}(a) \neq \emptyset$
    - a does not make any of g's literals false
      - $g^+ \cap \text{effects}^-(a) = \emptyset$
      - $g^- \cap \text{effects}^+(a) = \emptyset$
- If a is relevant for g, then
  - $\gamma^{-1}(g,a) = (g - \text{effects(a)}) \cup \text{precond}(a)$

Backward-search(O, s_0, g)
    $\pi \leftarrow$ the empty plan
    loop
        if s_0 satisfies g then return π
        $A \leftarrow \{a | a$ is a ground instance of an operator in O
                and $\gamma^{-1}(g, a)$ is defined$\}$
        if $A = \emptyset$ then return failure
        nondeterministically choose an action $a \in A$
        $\pi \leftarrow a.\pi$
        $g \leftarrow \gamma^{-1}(g, a)$

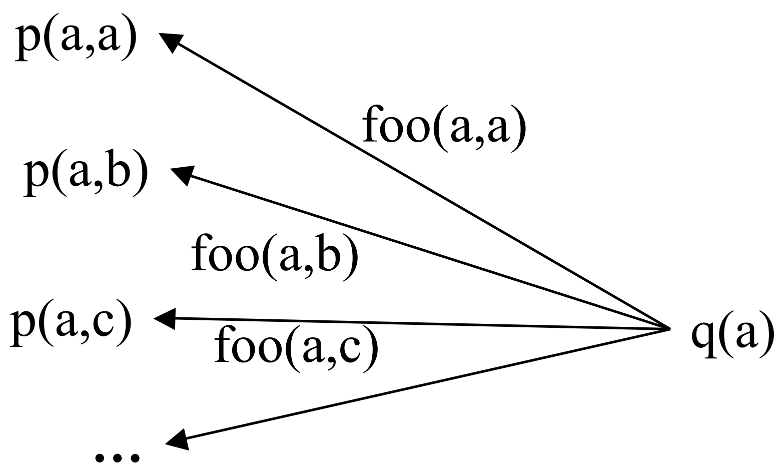


Efficiency of Backward Search



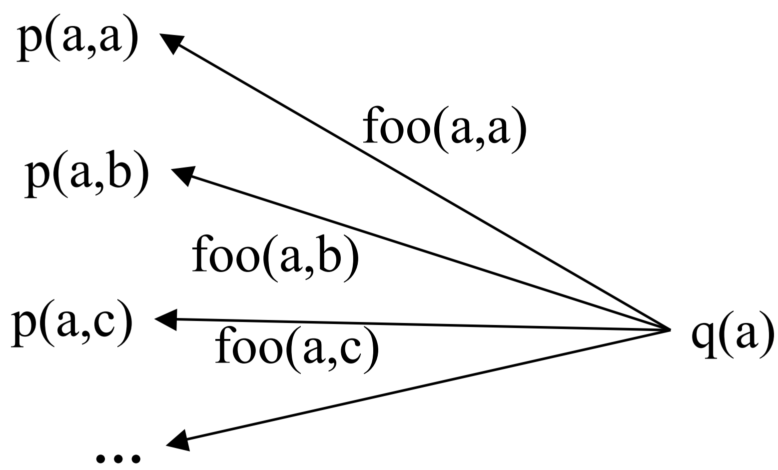
- Backward search's branching factor is small in our example
- There are cases where it can still be very large
  - Many more operator instances than needed

foo(x,y)
  precond: p(x,y)
  effects: q(x)

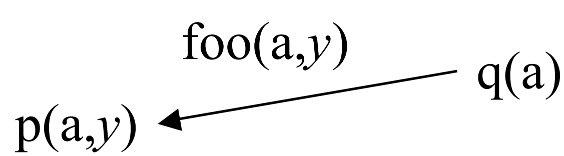


Lifting

foo(x,y)
  precond: p(x,y)
  effects: q(x)



- Can reduce the branching factor if we *partially* instantiate the operators
  - this is called *lifting*



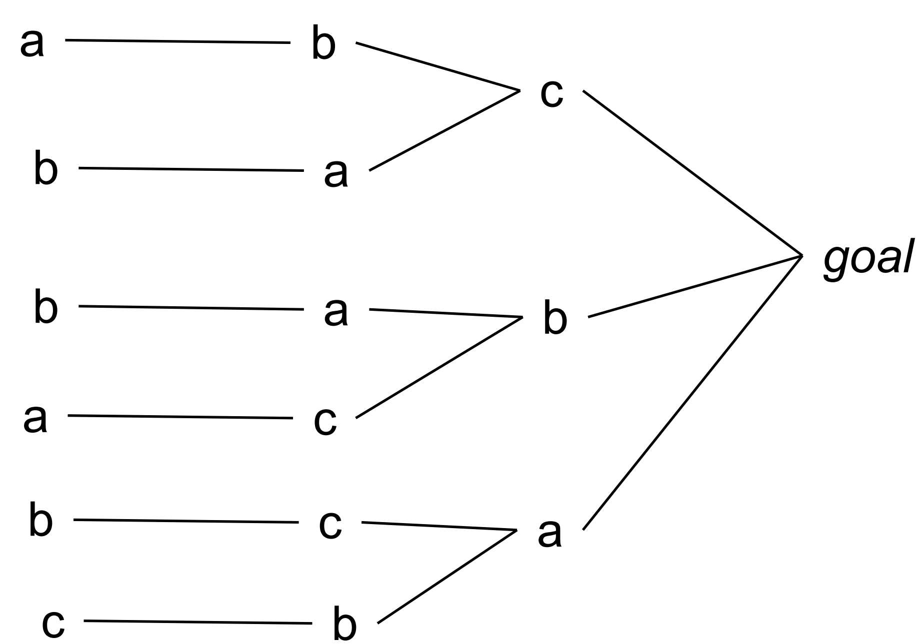
Lifted Backward Search

- More complicated than Backward-search
  - Have to keep track of what substitutions were performed
- But it has a much smaller branching factor

```
Lifted-backward-search(O, s_0, g)
    π ← the empty plan
    loop
        if s_0 satisfies g then return π
        A ← {(o, θ) | o is a standardization of an operator in O,
                 θ is an mgu for an atom of g and an atom of effects⁺(o),
                 and γ⁻¹(θ(g), θ(o)) is defined}
        if A = ∅ then return failure
        nondeterministically choose a pair (o, θ) ∈ A
        π ← the concatenation of θ(o) and θ(π)
        g ← γ⁻¹(θ(g), θ(o))
```

The Search Space is Still Too Large

- Lifted-backward-search generates a smaller search space than Backward-search, but it still can be quite large
  - If some subproblems are independent and something else causes problems elsewhere, we'll try all possible orderings before realizing there is no solution
  - More about this in Chapter 5 (Plan-Space Planning)



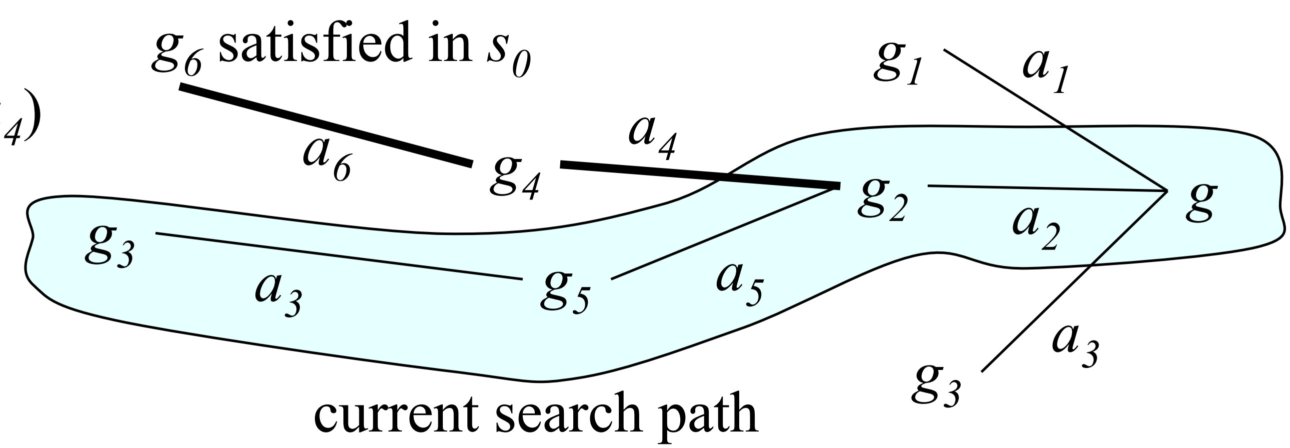
Other Ways to Reduce the Search

- *Search-control strategies*
  - I’ll say a lot about this later
    - Part III of the book
  - For now, just two examples
    - STRIPS
    - Block stacking

STRIPS

- $\pi \leftarrow$ the empty plan
- do a modified backward search from g
  - instead of $\gamma^{-1}(s,a)$, each new set of subgoals is just precond(a)
  - whenever you find an action that's executable in the current state, then go forward on the current search path as far as possible, executing actions and appending them to π
  - repeat until all goals are satisfied

$\pi = \langle a_6, a_4 \rangle$
$s = \gamma(\gamma(s_0, a_6), a_4)$



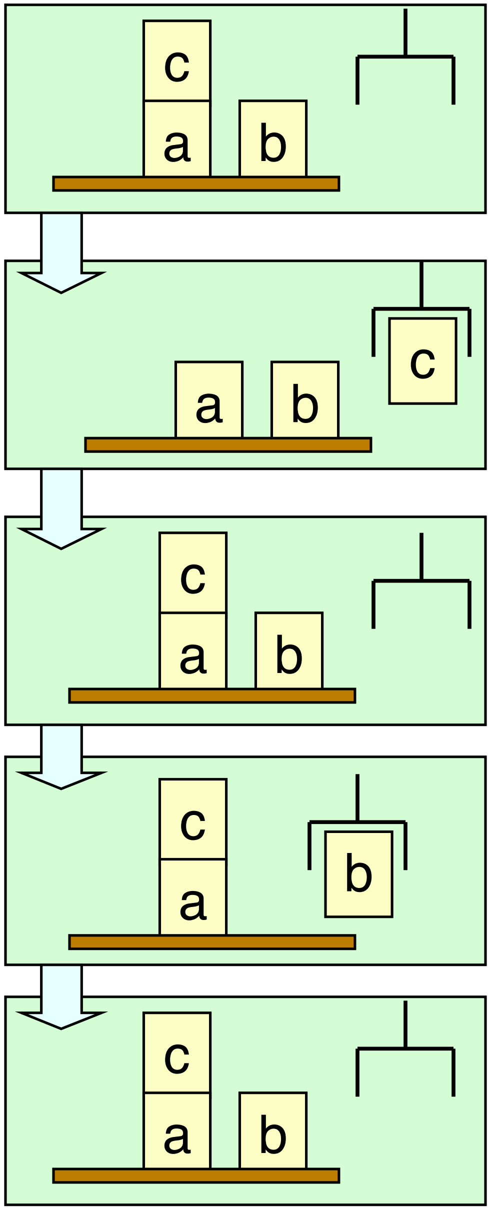
Quick Review of Blocks World

unstack(x,y)
Pre: on(x,y), clear(x), handempty
Eff: ~on(x,y), ~clear(x), ~handempty,
holding(x), clear(y)

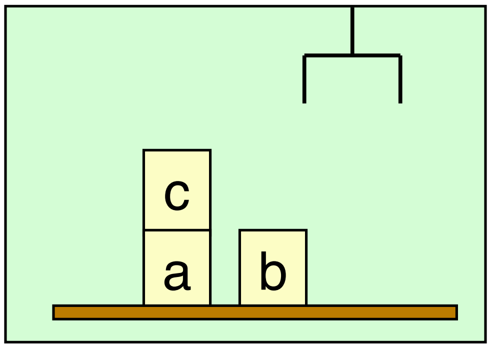
stack(x,y)
Pre: holding(x), clear(y)
Eff: ~holding(x), ~clear(y),
on(x,y), clear(x), handempty

pickup(x)
Pre: ontable(x), clear(x), handempty
Eff: ~ontable(x), ~clear(x), ~handempty, holding(x)

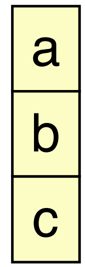
putdown(x)
Pre: holding(x)
Eff: ~holding(x), ontable(x), clear(?x), handempty



The Sussman Anomaly



Initial state



goal

- On this problem, STRIPS can't produce an irredundant solution
  - Try it and see

The Register Assignment Problem

- State-variable formulation:

  Initial state: {value(r1)=3, value(r2)=5, value(r3)=0}

  Goal: {value(r1)=5, value(r2)=3}

  Operator: assign(r,v,r',v')
  precond: value(r)=v, value(r')=v'
  effects: value(r)=v'

- STRIPS cannot solve this problem at all

How to Fix?

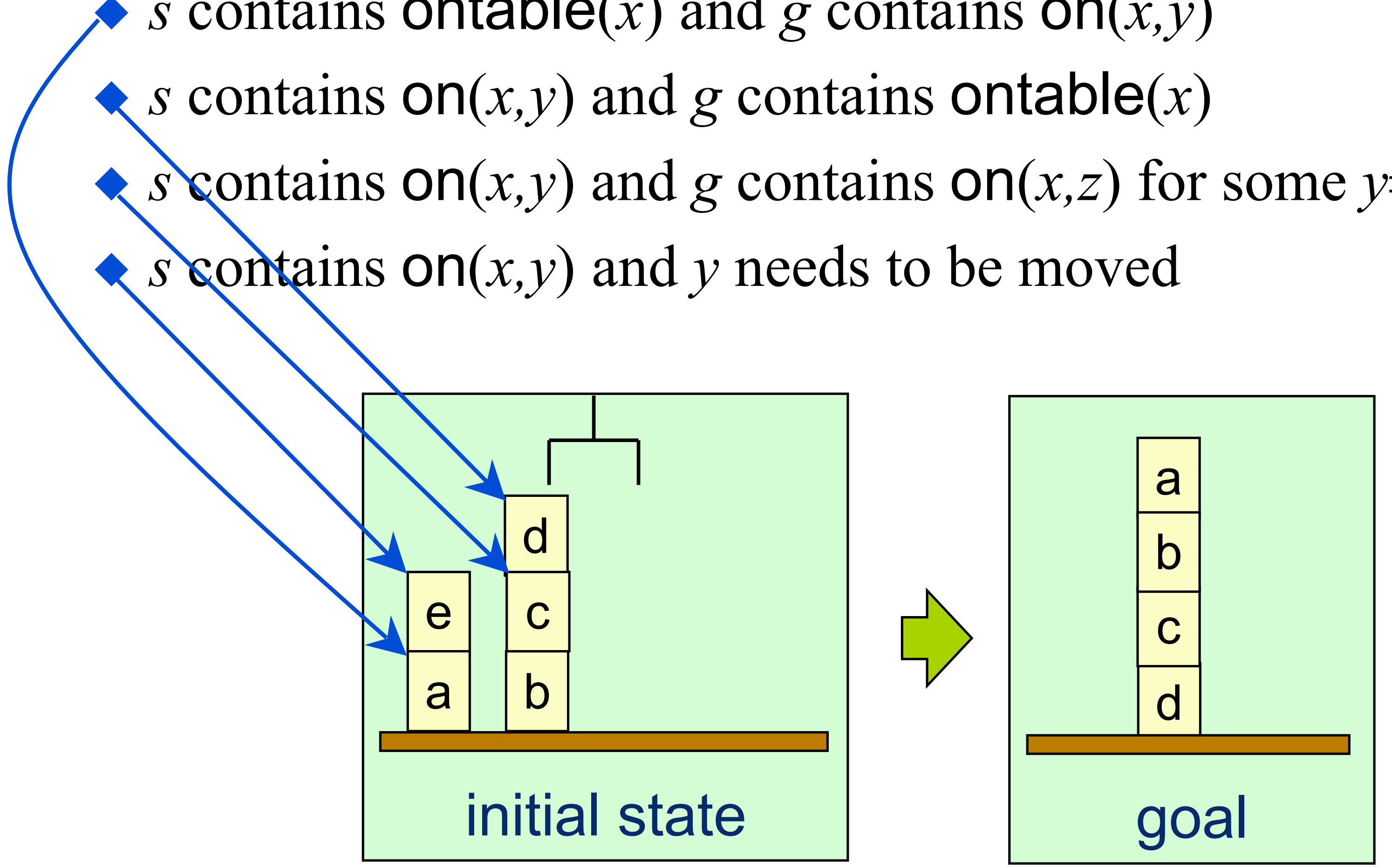
- Several ways:
  - Do something other than state-space search
    - e.g., Chapters 5–8
  - Use forward or backward state-space search, with *domain-specific* knowledge to prune the search space
    - Can solve both problems quite easily this way
    - Example: block stacking using forward search

Domain-Specific Knowledge

- A blocks-world planning problem $P = (O,s_0,g)$ is solvable if s_0 and g satisfy some simple consistency conditions
  - » g should not mention any blocks not mentioned in s_0
  - » a block cannot be on two other blocks at once
  - » etc.
    - Can check these in time O(n log n)
- If P is solvable, can easily construct a solution of length O(2m), where m is the number of blocks
  - Move all blocks to the table, then build up stacks from the bottom
    - » Can do this in time O(n)
- With additional domain-specific knowledge can do even better …

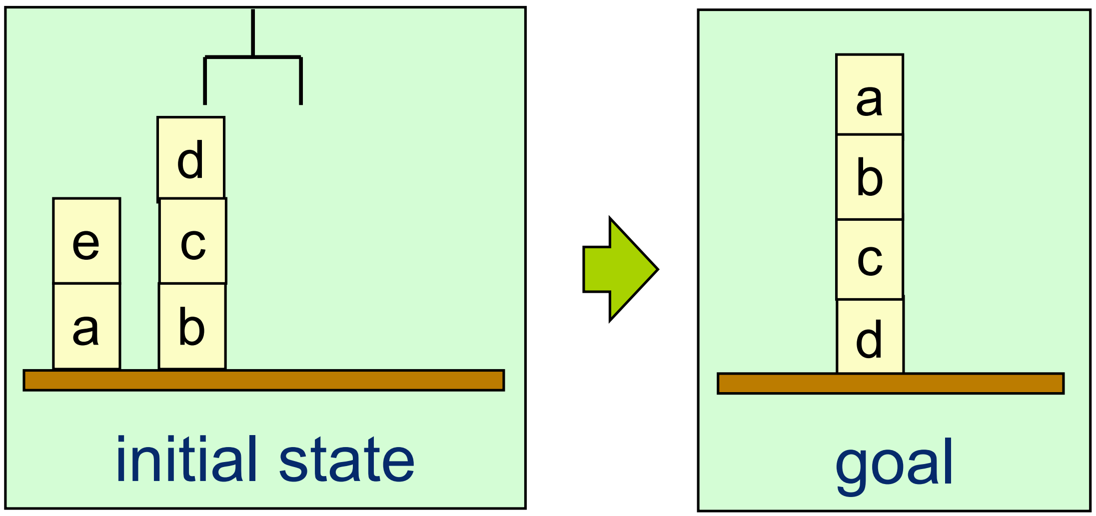
Additional Domain-Specific Knowledge

- A block x needs to be moved if any of the following is true:
  - s contains ontable(x) and g contains on(x,y)
  - s contains on(x,y) and g contains ontable(x)
  - s contains on(x,y) and g contains on(x,z) for some $y \neq z$
  - s contains on(x,y) and y needs to be moved



Domain-Specific Algorithm

loop
    if there is a clear block *x* such that
            x needs to be moved **and**
            x can be moved to a place where it won't need to be moved
        then move *x* to that place
    else if there is a clear block *x* such that
            x needs to be moved
        then move *x* to the table
    else if the goal is satisfied
        then return the plan
    else return failure
repeat



Easily Solves the Sussman Anomaly

loop
    if there is a clear block *x* such that
            x needs to be moved **and**
            x can be moved to a place where it won't need to be moved
        then move *x* to that place
    else if there is a clear block *x* such that
            x needs to be moved
        then move *x* to the table
    else if the goal is satisfied
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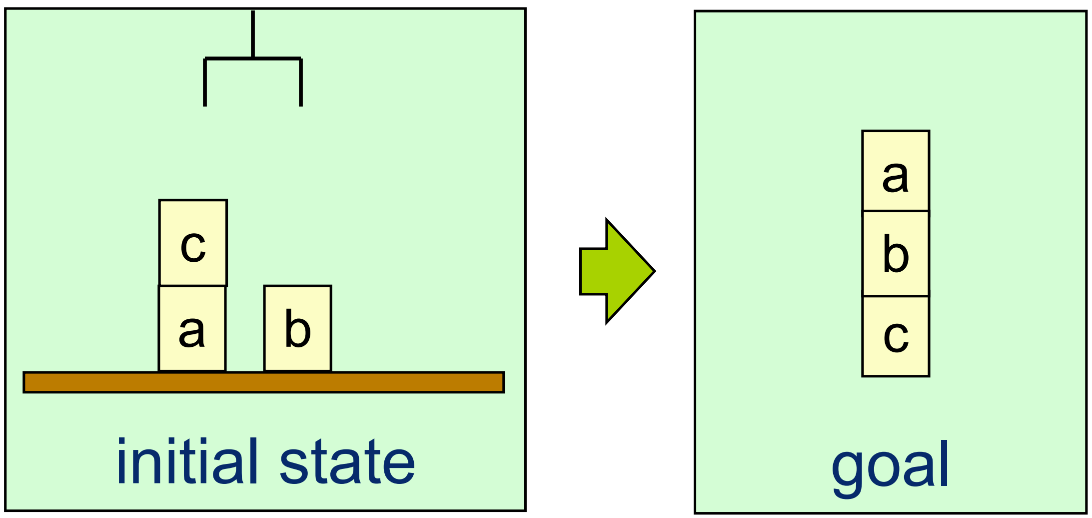
    else return failure
repeat



Properties

- The block-stacking algorithm:
  - Sound, complete, guaranteed to terminate
  - Runs in time $O(n^3)$
    - Can be modified to run in time $O(n)$
  - Often finds optimal (shortest) solutions
  - But sometimes only near-optimal (Exercise 4.22 in the book)
    - Recall that PLAN LENGTH is NP-complete